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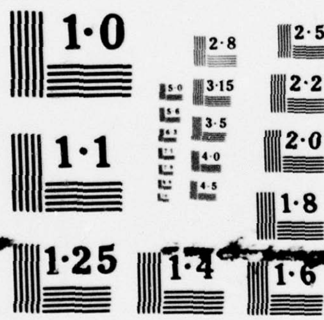
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/ESTIGATIONS OF THE USE OF CONVENTIONAL FILMS IN THE ETL CARTOGRAPHIC EBR

Image Graphics, Incorporated

107 ARDMORE STREET, FAIRFIELD, CT. 06430

15 March 1979

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Prepared for

U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES
Fort Belvoir, Virginia 22060

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Conventional photographic films sensitive to electrons may be used in the ETL Cartographic EBR provided that image distortions caused by deflection of the electron beam due to electric charge accumulation on the film is within acceptable limits. Various techniques for minimizing film charging problems were investigated and practical solutions are discussed.

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Preface

The work described in this report was authorized by the United States Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, 22060, under Contract No. DAAK70-77-C-0163 and was conducted by Image Graphics, Inc. with Andrew A. Tarnowski as the Principal Investigator.

The contract was performed under the technical direction of the Automated Cartography Branch, Mapping Developments Division, United States Army Engineer Topographic Laboratories under the direction of Howard Carr. Fred Merkel served as the Project Engineer for the Government.

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1. Introduction

The Cartographic Electron Beam Recorder (EBR) System developed by Image Graphics, Inc. for the U.S. Army Engineer Topographic Laboratories under Contract DAAG53-75-C-0221 makes use of a special electron recording film: Kodak Direct Electron Recording Film, Type SO-219. Since this film is approximately four times more expensive than some conventional, low cost, photographic films, an investigation was undertaken to determine whether any commercially available film, less expensive than SO-219, could be used in the Cartographic EBR.

2. Film Cost Analysis

For the purpose of this analysis, it is assumed that in production a single Cartographic EBR, recording 8 X 5 inch images, on 5½ inch wide film, for 8 hours per day, 5 days per week, at a rate of about 40 images (frames) per hour, would consume approximately 70,000 lineal feet of 5½ inch wide film per year. Recent quotes received from the Eastman Kodak Co. indicate a price of $69.95 per roll for 100 ft. rolls of 5½ inch wide SO-219 film. Thus the yearly costs for the Master Recording Film for a single production EBR would be approximately $50,000. Yearly film costs could be reduced to less than $12,000, if low cost films, such as for example Kodak Type SO-438, could be used.

The high cost of SO-219 film is due primarily to two factors: a) low volume production and b) complexity of manufacture; SO-219 film is provided with a special electrically conducting layer to prevent the accumulation of electric charges.

3. Electric Charging of the Recording Film

There is comparatively little published information on problems associated with the accumulation of electric charges on the recording film in electron beam recording (See References) and even less information is available on practical techniques which might lead to the reduction or elimination of these problems. The main reason for this situation is that, from a technical point of view, the ideal way of eliminating all film charging problems in electron beam recording is to provide the recording film with sufficient electrical conductivity. This has been done by film manufacturers, but has lead to a disproportionate increase in film costs.

The accumulation of electric charges on the recording film in an EBR can be caused by either (a) triboelectric effects, ie. charging by friction and (b) the deposition of electrons on the film by the recording beam itself. A study of the generation of triboelectric charges on photographic films is beyond the scope of this investigation, however, an appreciation of triboelectricity, as it affects films and film handling operations, is of importance in

selecting films and film transport mechanisms for electron beam recording. The appendix to this report, reproduced from Kodak Publication No. M-63, provides much practical information on the subject.

No matter how the electric charging of the recording film in an EBR is produced it can give rise to various types of problems such as: a) Geometric or positional image distortions b) Spurious changes in image resolution c) Variation in optical density of the recorded image d) "Static" marks on the film e) Mechanical difficulties in transporting the film due to Coulomb forces between the charged film and its surroundings. Examples of such problems (grossly exaggerated for demonstration purposes) are shown in Figures 1,2,3 and 4. Neither "static" marks, nor difficulties with transporting the film due to Coulomb forces have actually been encountered in the normal operation of the ETL Cartographic EBR. It is the problem of geometric image distortions, or positional displacements of recorded images, which must be regarded as most critical as far as the ETL Cartographic EBR is concerned.

4. Theoretical Considerations

Volume and surface resistivity of photographic films are very high. The volume resistivity of polyester film support (generally used in electron beam recording)

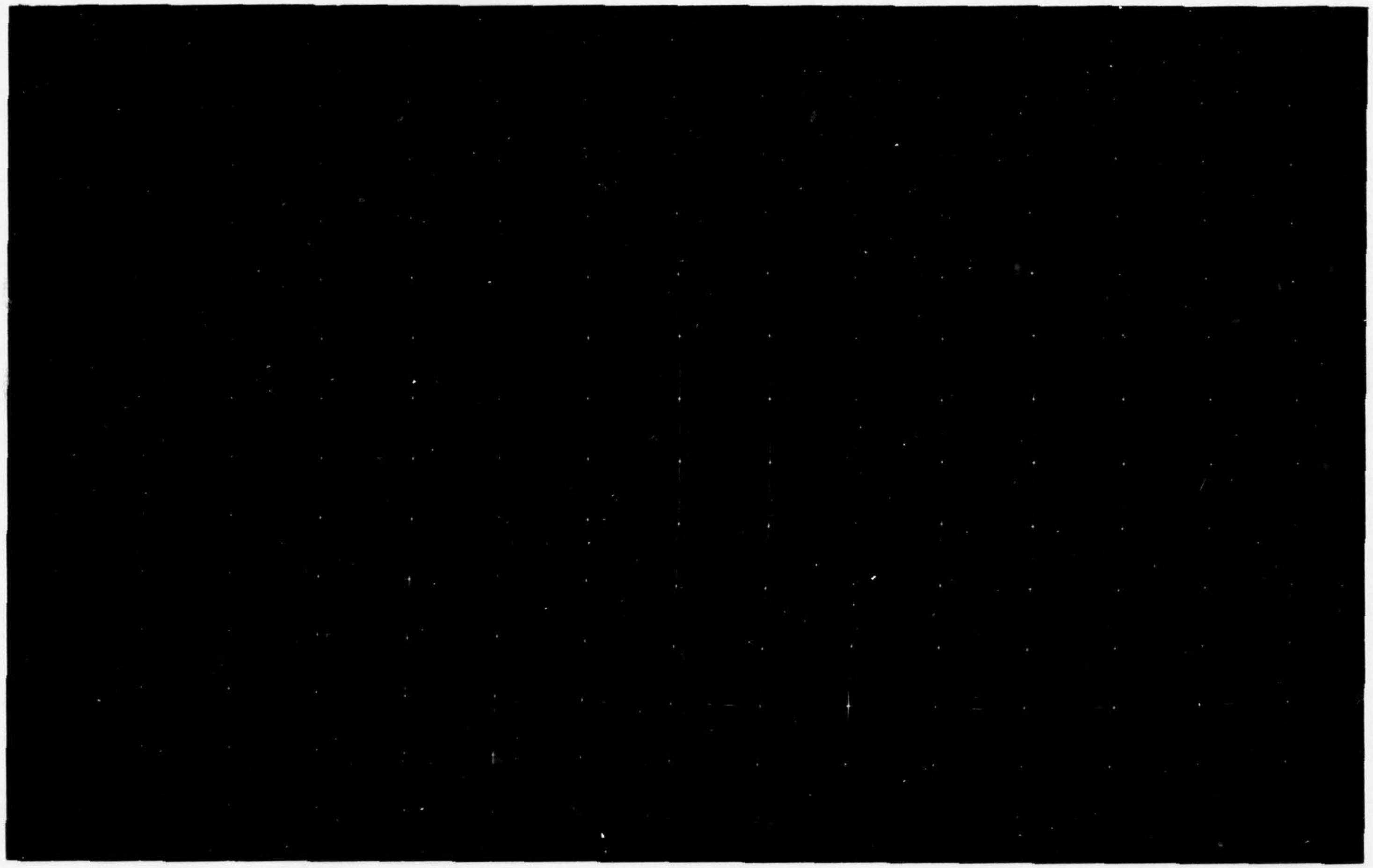

Figure 1. Geometric distortions of a rectilinear grid pattern, recorded in the ETL Cartographic EBR, caused by electrostatic charging of the recording film.

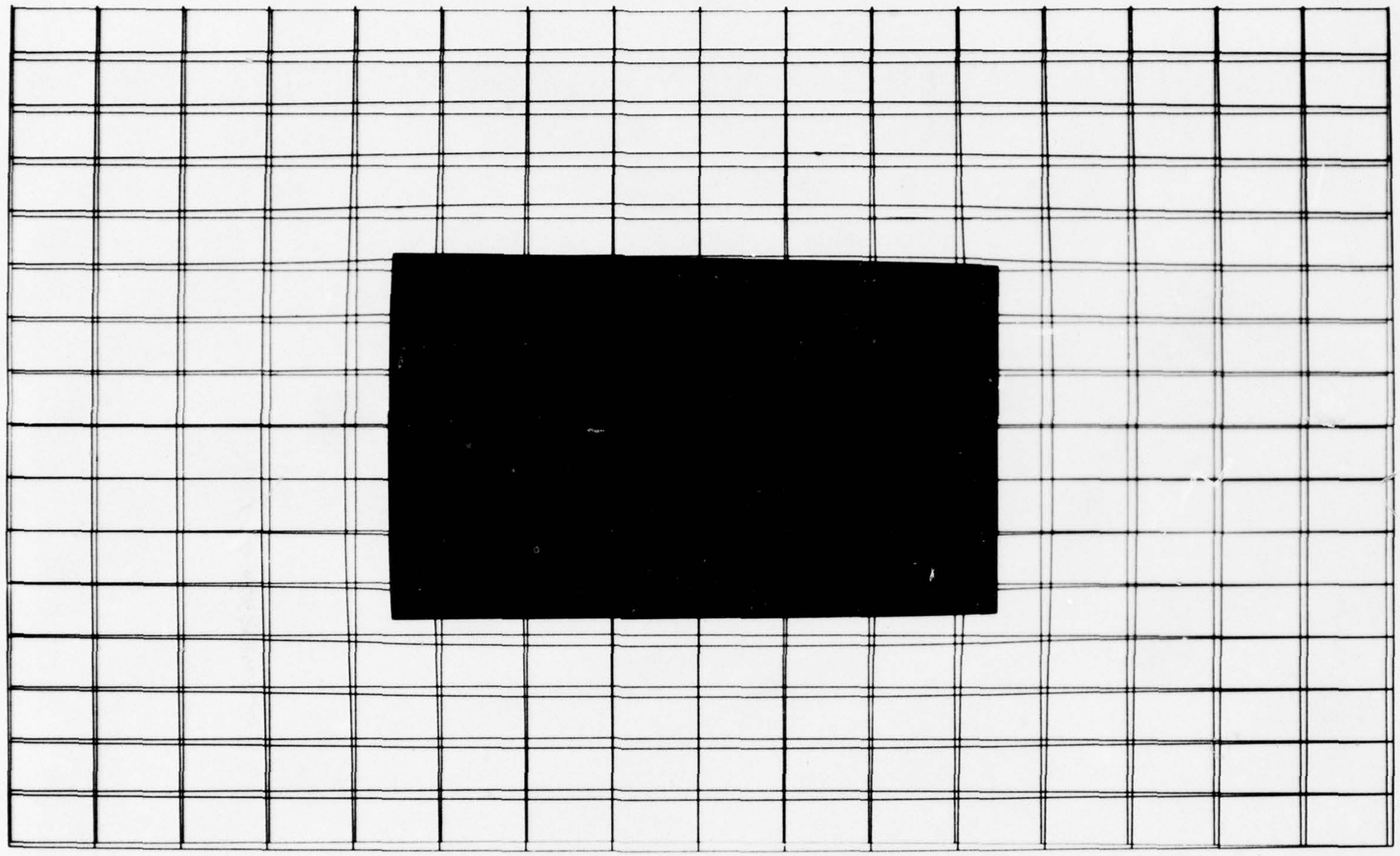

Figure 2. Geometric distortions of the grid pattern are caused by the heavy exposure in the central rectangle. Also note the trapezoidal distortion of the rectangle.

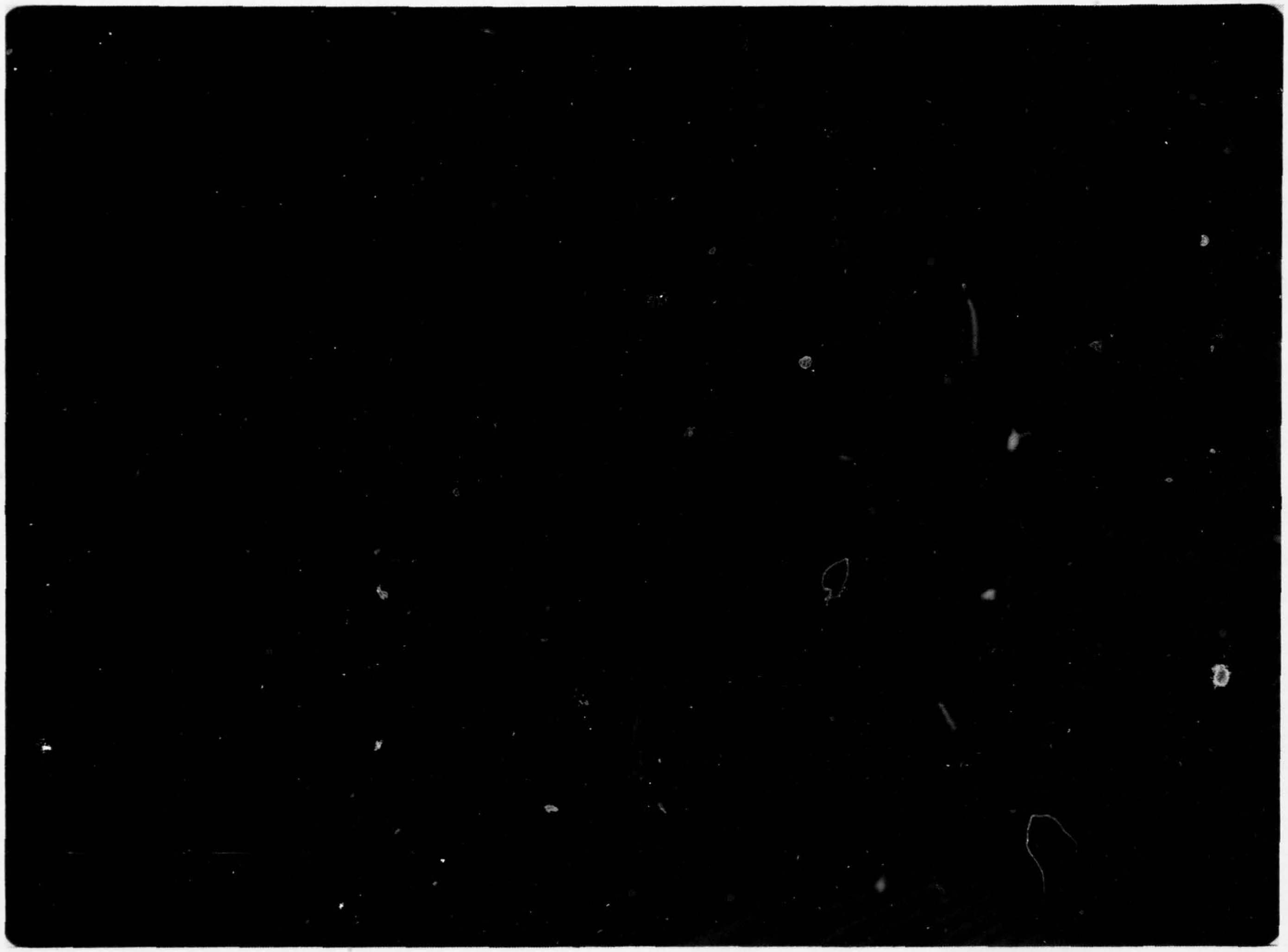

Figure 3. Density variations in uniformly exposed areas are caused by variations in electric potential which in turn are caused by local variations of the recording film capacitance.

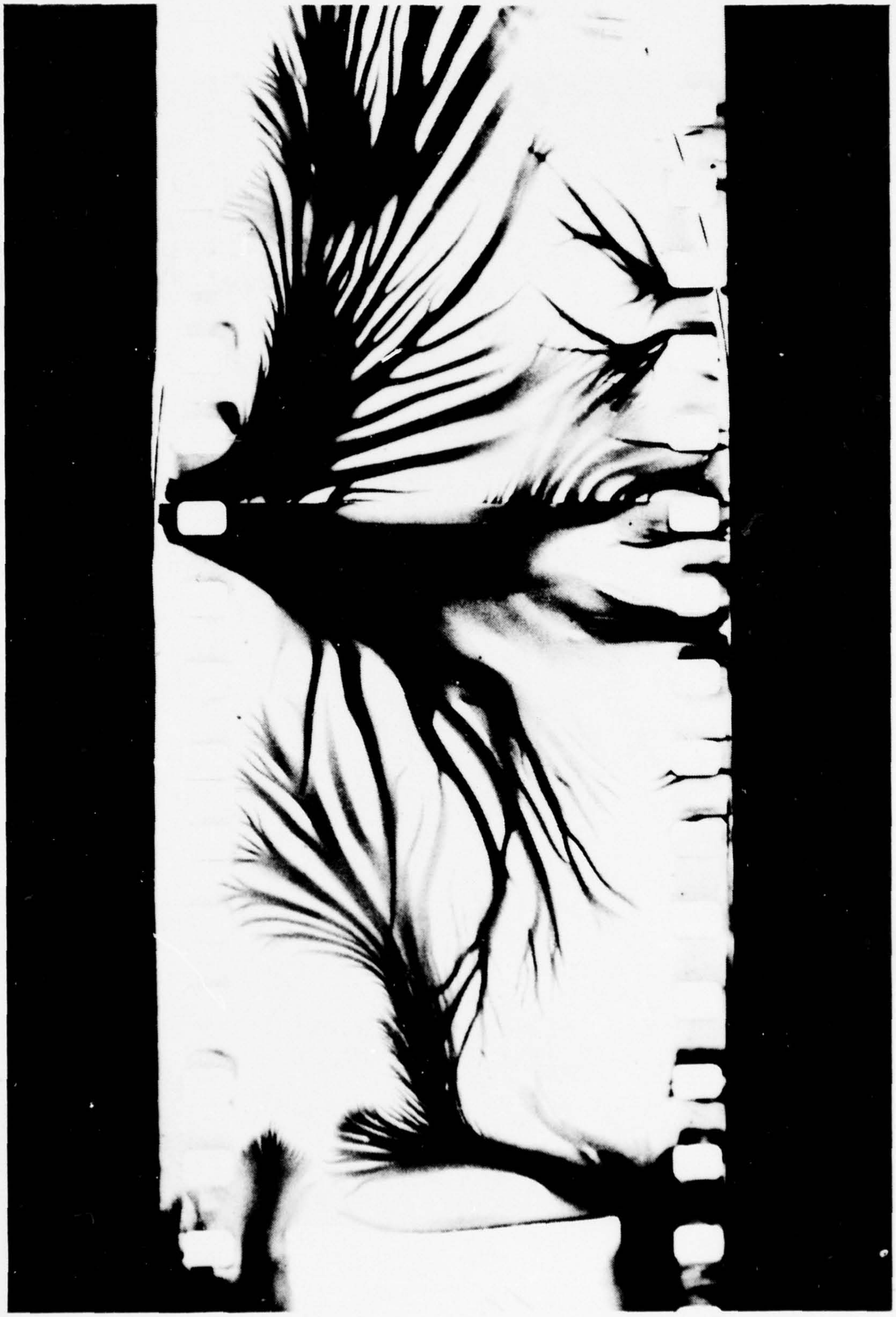

Figure 4. Static marks on 35 mm film, without conductive layer, run in a high speed EBR.

is in the order of 10^{18} ohm-cm, whereas the surface resistivity of photographic emulsions, particularly when dried out in the vacuum environment of an EBR, is usually greater than 10^{12} ohms per square. Thus, unless provided with special conducting layers, photographic films used in electron beam recording must be considered as excellent electric insulators which will not dissipate any electric charge they may acquire.

Most problems associated with film charging in electron beam recording are directly dependent on the magnitude of the electrostatic potentials present on the recording film. Since Potential (V) is proportional to Charge (Q) and inversely proportional to Capacitance (C), i.e.

$$V = \frac{Q}{C}$$

film charging problems in EBRs can be minimized either by reducing the electric charge (i.e. the exposing beam current) or by increasing the effective electric capacitance of the recording film.

If the back surface of the recording film in an EBR is electrically grounded by being held in intimate contact with a metal surface, (such as, for example, the pressure platen of the film transport mechanism) then the effective electric capacitance of the emulsion layer of the film is given by the expression

$$C = \frac{0.0885 \times k \times A}{t}$$

where C = Capacitance in picofarads; A = Film area in cm^2; t = Film thickness in cm; k = Dielectric constant of the film. The thickness of films typically used in the Cartographic EBR is 0.004 inches (0.01 cm) and the dielectric constant of such films (i.e. polyester base) is typically 3.1, thus the effective capacitance of these films is approximately 27 picofarads per cm^2.

Figure 5 shows the sensitometric characteristics of some electron sensitive films, manufactured by the Eastman Kodak Co., that have been extensively used in electron beam recording. If these films had not been provided with special conducting layers and were uniformly exposed with a 15 KV electron beam so as to obtain an optical density of 1·0 after processing in D-19 for 4 minutes at 68^{o}F, the electric charge that would have been acquired by these films in the process of exposure would have been as shown in the second column of the table in Figure 5. Assuming that all four films have a 0.004 inch thick polyester support* (i.e. an effective capacitance of 27, pf/cm^2) the electrostatic potential acquired by these films, as a result of electron exposure, would be as shown in the third column of the table in Figure 5.

Knowing the magnitude and distribution of electrostatic potentials on the recording film in an EBR makes it theoretically possible to calculate all the resultant

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*SO-438 has an unusual support thickness of 0.0047 inch.

FILM TYPE	COULOMBS/cm²	VOLTS	MAX. % DISTORTION
SO-438	5×10^{-10}	18	0.06
SO-219	2.5×10^{-9}	93	0.31
SO-159	6×10^{-9}	222	0.75
SO-214	2×10^{-8}	741	2.56

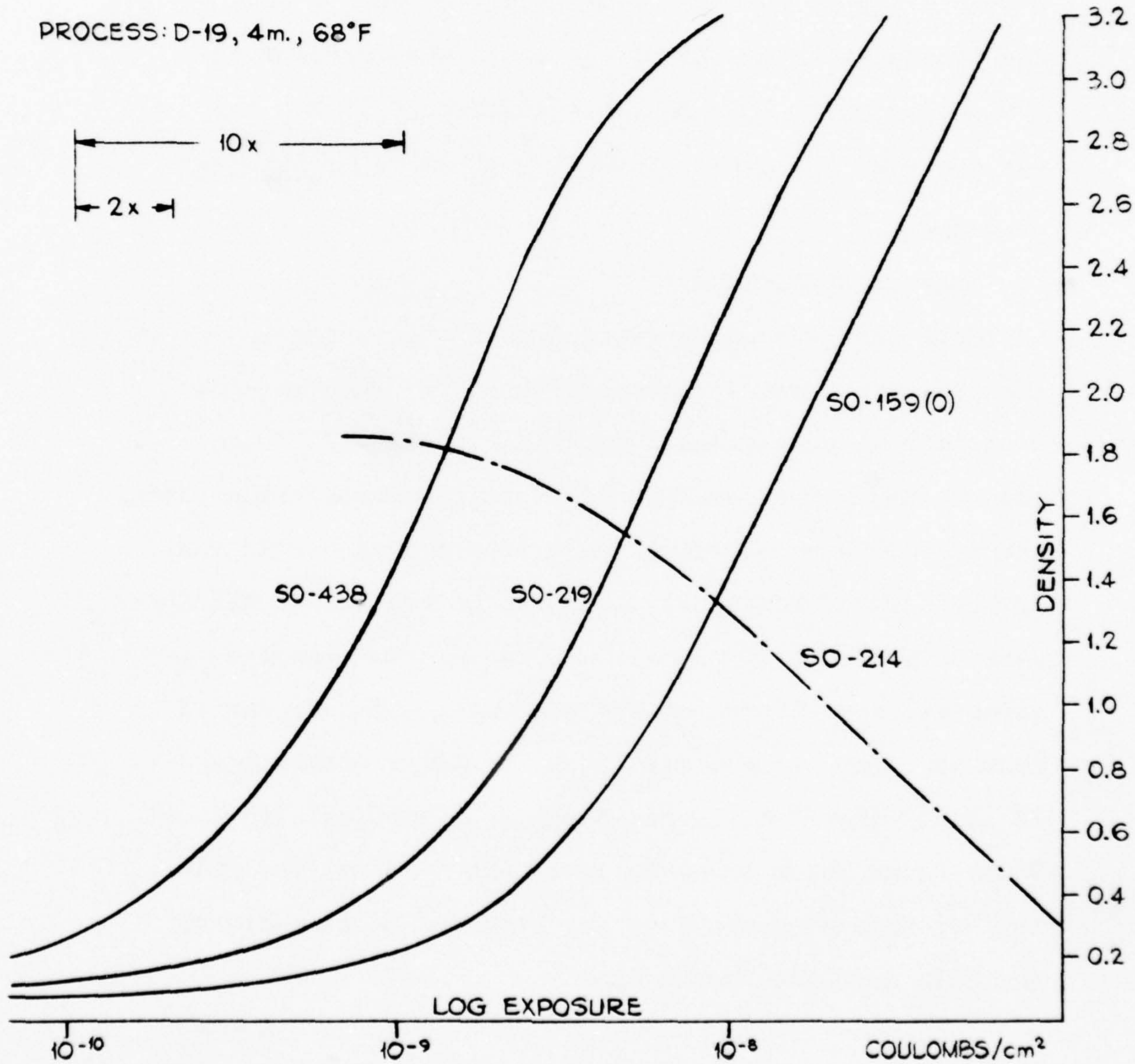

Figure 5. Sensitometric Characteristics of Electron Sensitive Films

geometric distortions in the recorded images; however, such calculations would be very difficult to perform. A simplified "worse case" analysis indicates that the maximum beam displacement (i.e. image distortion), that can be expected due to a potential V on the recording film equals $\sqrt{\frac{Z}{Z-V}}$ where Z is the electron beam accelerating potential. Thus, for example, if an electrostatic potential of 100 volts were present on the recording film in an EBR operating at 15 KV, the maximum expected image distortion would be $\sqrt{\frac{15,000}{15,000-100}}$ or 0·34%.

5. Experimental Tests

More than a hundred recordings of test pattern (of the type shown in Figures 1,2 and 3) were made on a variety of photographic materials in the ETL Cartographic EBR during the course of this investigation; some samples of these materials were provided by Mr. R. Anwyl of the Eastman Kodak Co. Exposure levels in the ETL/EBR were varied from 10^{-10} to 10^{-7} Coulombs/cm^2 and the effective capacitance of the recording film was varied from 43 pf/cm^2 (for 2½ mil Estar Thin Base) through 27 pf/cm^2 (for 4 mil Estar Base) and 15 pf/cm^2 (for 7 mil Estar Thick Base) to less than 5 pf/cm^2 for films held at some distance from any grounded metal parts of the film transport mechanism.

At the beginning of this investigation, various anomalies in the experimental results were observed. These anomalies were found to be due to spurious changes in the effective capacitance of the recording film and were brought about in the following manner: In the Cartographic EBR the recording film is clamped between the film gate frame (which has an 8 X 5 inch opening) and the pressure platen, shown in Figure 6. It could be thought that the back of the film would remain in good contact with the flat metal pressure platen and that, therefore, the front surface of the film (i.e. the emulsion layer) would have a uniform capacitance, strictly determined by the thickness and dielectric constant of the film. But in practice that was not found to be the case. Due to the existance in an EBR of slightly different degrees of vacuum on both sides of the film and due to the differential shrinkage rates of the emulsion layer and film base in a vacuum environment, significant buckling of the film may occur. Measurements made in the ETL Cartographic EBR indicate that although the recording film is properly clamped around the periphery of the film gate opening, the centre portions of the 8 X 5 inch film frame may become spaced as much as 10 to 30 mils from the pressure platen. The further the film is spaced from the pressure platen the lower its electric capacitance. In addition, the pressure platen

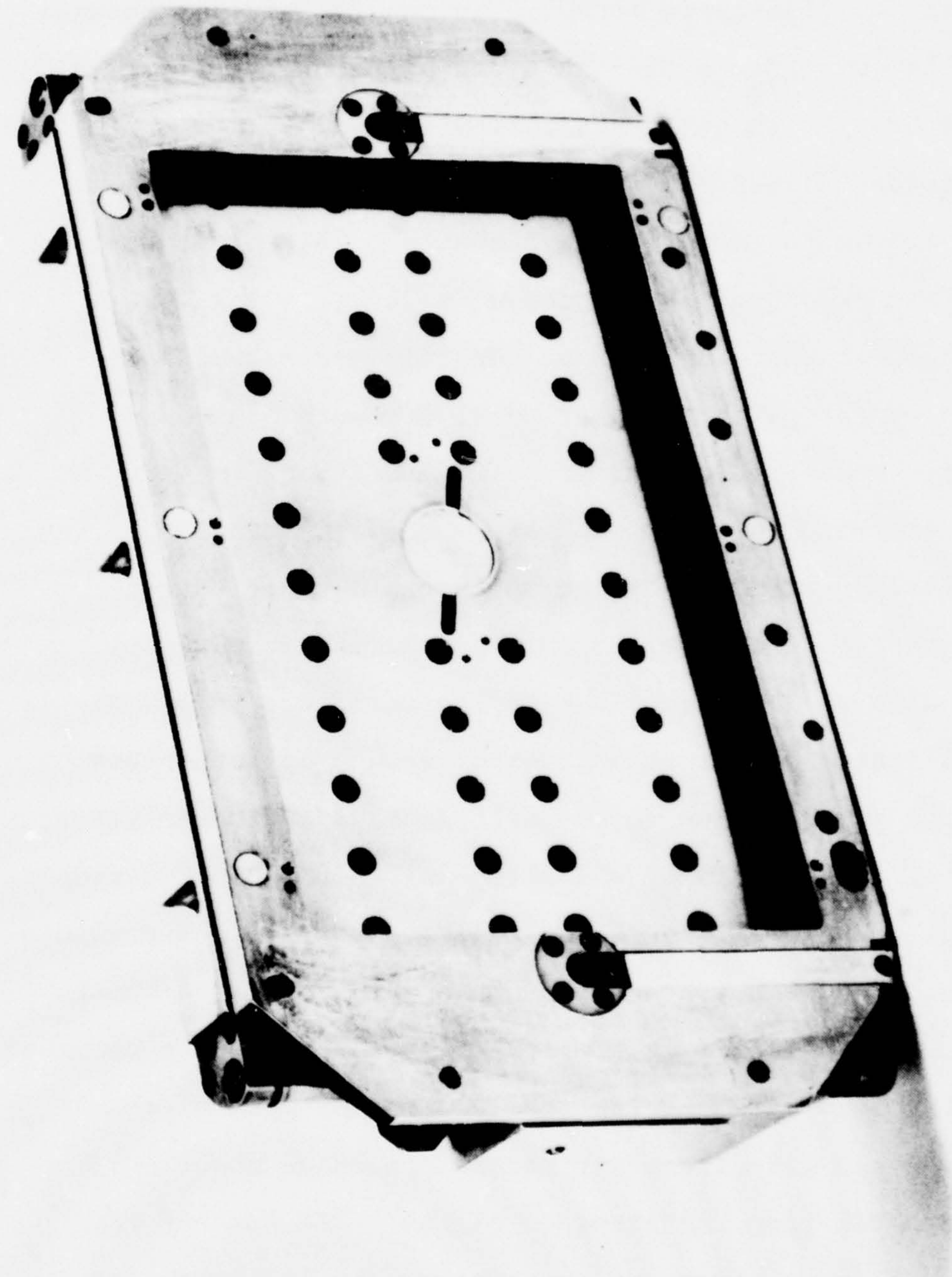

Figure 6. Film Gate of ETL Cartographic EBR

in the ETL Cartographic EBR had been provided with a number of large holes, (See Figure 6) consequently the capacitance of the recording film in the vicinity of these holes is much lower.

The capacitance of the recording film used in the ETL Cartographic EBR could readily be made consistent and uniform in three different ways: a) by coating the back of the recording film with a continuous layer of electrically conducting paint, b) by glueing 8 X 5 inch pieces of film to a flat metal plate which is then mounted in a special film holder, c) by using a cylindrically convex film gate,* shown in Figure 7, which ensures that the back of the film is always in intimate contact with a metal surface.

Using all three above mentioned techniques for ensuring uniform capacitance, it was demonstrated experimentally that all geometric image distortions or displacement resulting from the use of electrically non-conducting recording films in the ETL Cartographic EBR were in fact proportional to the exposing beam current and inversely proportional to the effective capacitance of the film.

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* of the type used in an IGI proprietary film transport mechanism for which a patent application has been made

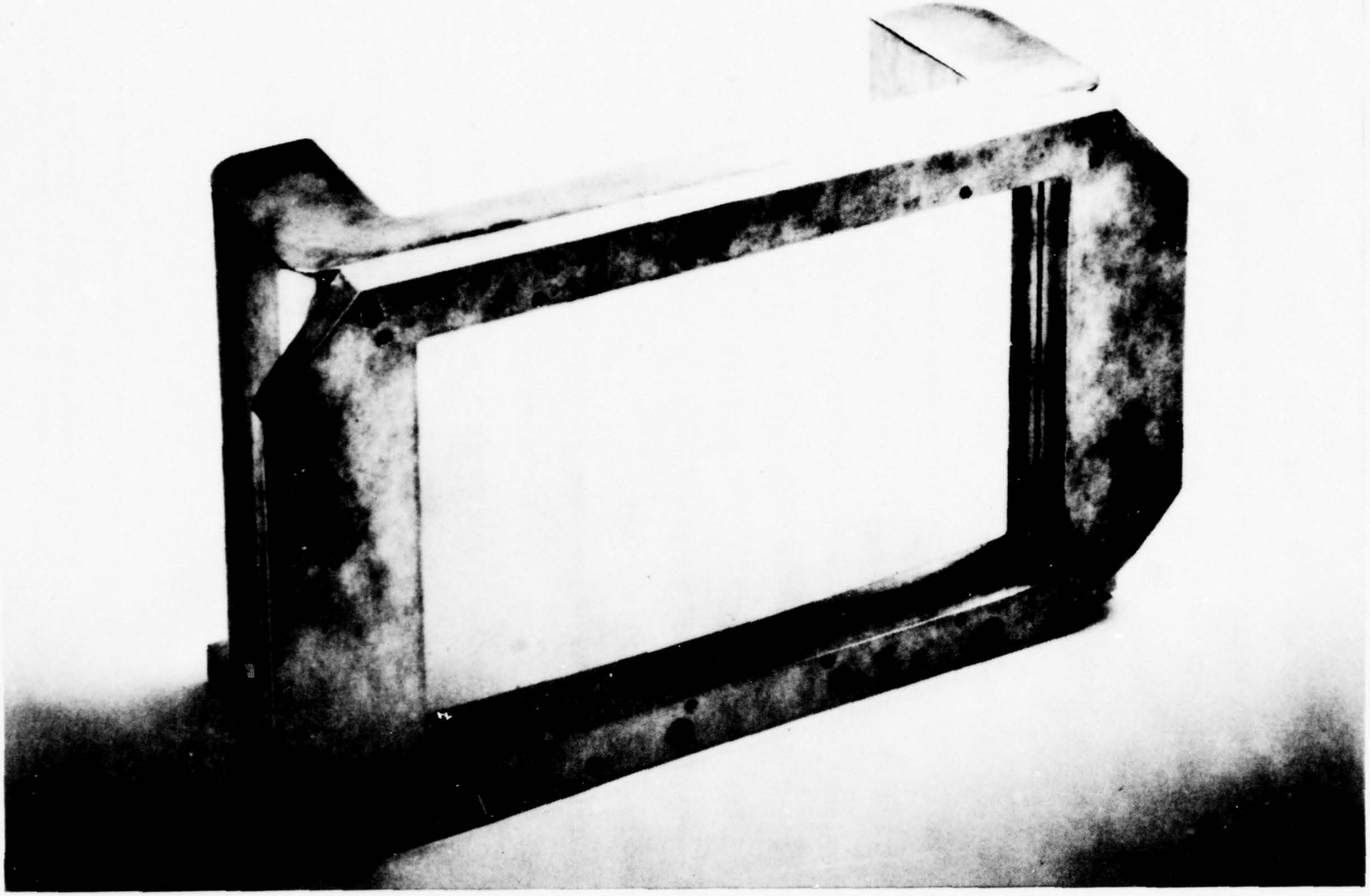

Figure 7. Cylindrically Convex film gate which can be mounted in the ETL Cartographic EBR.

6. Micromesh Screens

Another technique, which can be used to minimize film charging problems in electron beam recording, is to place a very fine micromesh in front of the film, thus shielding most of the electron beam path from electrostatic fields due to the electric charge on the recording film. The micromesh, which is normally held at the same potential as the film gate (i.e. at ground potential), can be mounted sufficiently far away from the film to be completely out of focus. Since a constant fraction of the beam current is intercepted by the micromesh, it could also conveniently be used for continuously monitoring and controling the beam current in an EBR.

There are several potential disadvantages of using a micromesh in an EBR: a) Since the micromesh must be extremely fine, it can easily be damaged and may have to be frequently replaced, b) The micromesh must always be perfectly clean; any spec of dirt on the micromesh will cast its "shadow" on every image recorded in the EBR, c) No matter how fine or transparent a micromesh is, it will always scatter a certain fraction of incident electrons causing some spurious exposure, or "fog", on the recording film.

Several micromesh screens, one of which is shown in Figure 8, were tested in the ETL Cartographic EBR. The meshes varied from 70 to 333 wires per inch and from

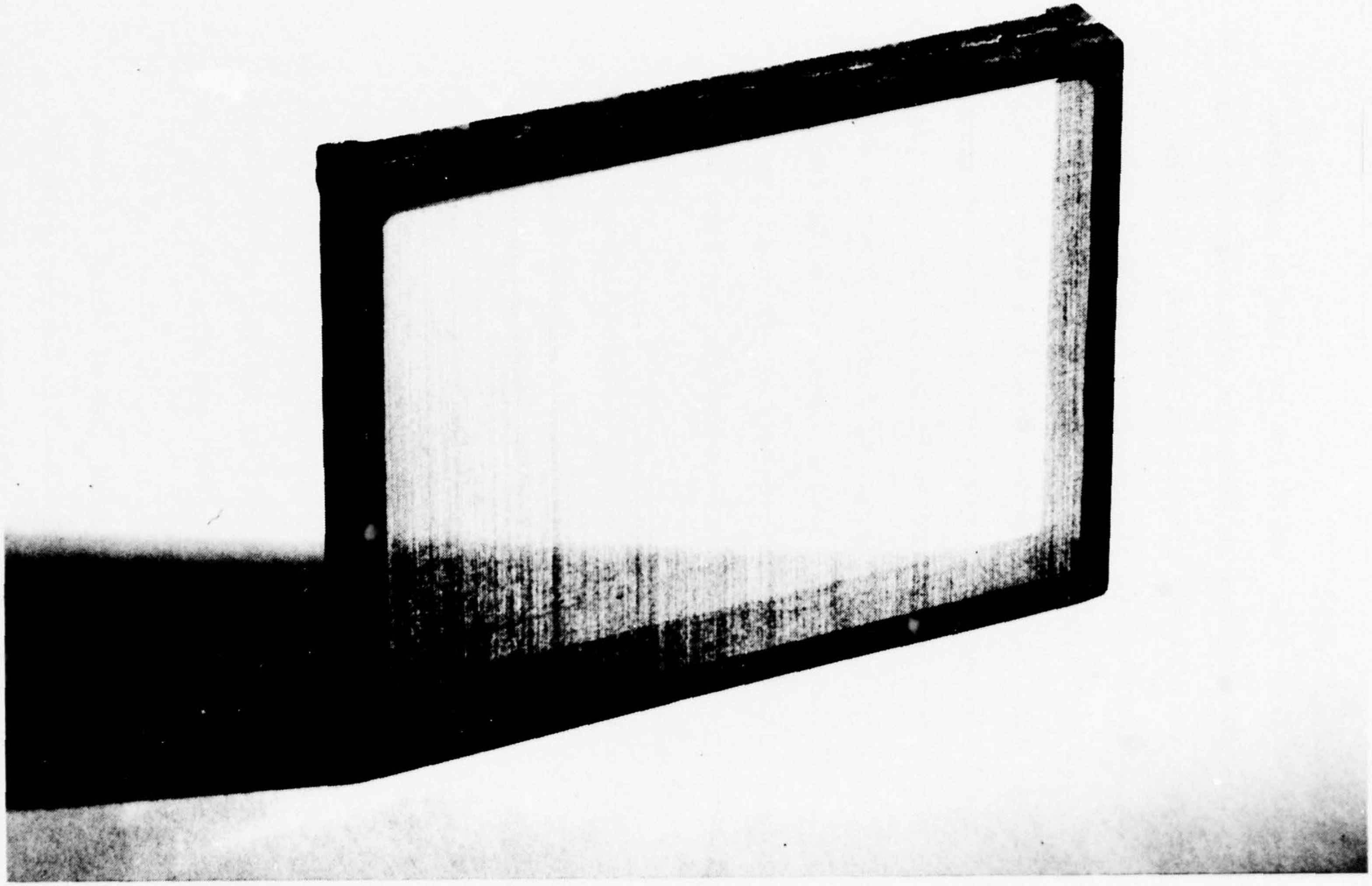

Figure 8. Micromesh screen mounted on frame which can be installed in the ETL Cartographic EBR.

90% to 60% in transmission.

When a micromesh is mounted very close to the recording film in the ETL Cartographic EBR, the spurious deflection of the electron beam due to the presence of charges on the film is reduced so effectively that it can no longer be measured. However, images recorded in the EBR with a micromesh in close proximity to the recording film show, under microscopic examination, a sharply focused shadow of the micromesh. As the micromesh is spaced further away from the recording film, its shadow in the recorded images becomes progressively less distinct but the attenuation of image distortions, due to charges present on the film, is correspondingly reduced.

A 333 wires per inch micromesh mounted in the ETL Cartographic EBR was considered totally out of focus when spaced approximately 1 inch from the recording film; but in such a location the micromesh reduced beam displacements due to charges on the film by no more than a factor of 4. It is expected that a 500 wires per inch micromesh (which is the finest mesh available in a 8 X 5 inch size) might be significantly more effective in reducing film charging problems, since it should remain completely out of focus when spaced considerably less than 1 inch from the recording film.

The spurious exposure, or "fog", produced by electrons scattered by the micromesh may, or may not, be regarded

as objectionable, depending on the type of imagery that is being recorded. Tests performed in the ETL Cartographic EBR show that under the most adverse conditions, (i.e. a large high density area surrounded by a totally clear area in the recorded image) the maximum spurious fog produced by a 60% transmission micromesh was 0·2 optical density units.

7. Film Conductivity

As stated in section 3 of this report, the ideal way of eliminating all film charging problems in electron beam recording is to provide the recording film with sufficient electrical conductivity. The degree of film conductivity required depends primarily on the recording rate (i.e. the exposure time) in the EBR.

Photographic film consists basically of a very thin layer of silver halide emulsion coated onto a transparent substrate. As far as this investigation is concerned only one substrate need be considered, namely, the dimensionally stable, 4 mil thick, polyester support which is normally used in EBR's. Since the film support is an extremely good insulator, it will be assumed at first, that the emulsion layer can somehow be made electrically conducting. The question then arises as to how conducting the emulsion layer should be to eliminate film charging problems for a given electron beam recording application.

The maximum recording rate currently being considered for the ETL Cartographic EBR is 100 Megapixels per second, with a pixel size of about 5 μm. Thus the time to expose 1 cm^2 of film, at this maximum recording rate, would be 1/25 of a second.

Film charging problems in an EBR may be regarded as eliminated if the conductivity of the emulsion layer is sufficient to reduce any electrostatic potential that would have been acquired by the film (in the absence of any conductivity) to 1% of its value. Since the potential on a capacitor (C) paralleled by a resistor (R) decays exponentially to 1% of its original value in a time equal to 4·6RC, the resistivity of the emulsion layer required to eliminate film charging problems in the ETL Cartographic EBR should be of the order of 3×10^8 ohm per square, or less.

$R = T/4{\cdot}6C$, where $T = 1/25$ sec. and $C = 27$ picofarads

8. Conductive Layers

In the manufacture of special photographic films for electron beam recording, electrical conductivity is usually provided not by making the emulsion itself conducting, but by coating an additional conductive layer onto the film. The conductive layer can be located on top of the emulsion layer, or between the emusion layer and the film support, or on the back of the film support. In the case of SO-219 film, used in the ETL Cartographic EBR, the conductive layer is sandwiched between the emulsion layer and the film support.

To eliminate film charging problems in electron beam recording the most effective location for the conductive layer is on top of the emulsion. A layer thus located must be very thin, very uniform, not affected by exposure to vacuum or air regardless of humidity and not affected by mechanical contact with the back of the film when the film is wound in a roll. The resistivity of such a conductive layer should be of the order of 10^8 ohms per square or less (See Section 7), its thickness should not be greater than, say, 1% of the electron penetration*, but the layer need not be highly transparent if it is removed during film processing.

If the conductive layer is located between the film support and the emulsion layer it will be almost as effective as if located on top of the emulsion layer, provided that the thickness of the emulsion layer is no greater than the electron penetration.* In other words, provided that the electron beam has sufficient energy to penetrate right through the emulsion layer to the conductive layer. A conductive layer located between the emulsion layer and the film support has to be very clear and very uniformly transparent since it is not removable during film processing, but its thickness is comparatively uncritical.

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* For 15KV electrons electron penetration corresponds to an emulsion coating weight of approximately 0.6 mg/cm^2

If the conductive layer is coated on the back of the recording film, it will not reduce film charging problems due to the deposition of electric charge by the recording beam itself; however, such a layer would be beneficial in eliminating film charging problems due to triboelectric effects (see appendix). A conductive layer on the back of the film need not be particularly thin, nor uniform, nor does it need to be transparent if it is removed during film processing; consequently, it may be possible to provide a conductive layer on the back of an EBR film without significantly increasing the manufacturing costs of such a film.

In the last few years significant technological advances have been made in coating electrically conductive layers on various film substrates. This is well exemplified by the photoconductive or dielectric recording films which have very recently become available from several manufacturers. It is believed that such technological advances will lead to improved quality, higher yield and reduced manufacturing costs for EBR films.

9. Conclusion

Results of this investigation indicate that some commercially available, high resolution, photographic films (such as SO438 which is not provided with a special electrically conducting layer) can be used in the ETL Cartographic EBR for the less exacting recording applications, if the film transport is modified. In addition, if some minor changes could be made to currently

available recording films, certain types of cartographic recording could adequately be made in a production EBR on films which should be significantly less expensive than SO-219. It must be emphasized that some of the more critical EBR applications, which are being investigated at ETL, would still mandate the use of either SO-219 film, or equivalent films possessing sufficient electrical conductivity.

10. Recommendations

This investigation has led to a better understanding of problems associated with the use of conventional films in the ETL Cartographic EBR. Consequently, a number of recommendations can be made; some of these recommendations apply specifically to the ETL/EBR, whereas others are more general in character.

a) The ETL Cartographic EBR should be provided with an IGI curved gate film transport. This recommendation is already being implemented under Contract DAAK70-77-C-0211.

b) Provisions should be made for mounting a very fine micro-mesh screen in the ETL Cartographic EBR.

c) If films not provided with special conductive layers are to be used in any EBR, the film transport of such an EBR should be designed so that: 1) the entire film gate is fabricated of

electrically conducting materials (i.e. metal not plastic) and is properly grounded. 2) the film gate surface in contact with the back of the recording film is smooth and devoid of any holes or other irregularities.

d) An investigation should be undertaken to determine if the ETL Cartographic EBR could be modified to operate at higher accelerating potentials, since geometric image distortions due to film charging problems are inversely proportional to the square root of the accelerating potential. Operating an EBR at higher accelerating potentials may also be of significance if reversal processing of EBR films is considered.

e) The practicality of using very thin films (1½ or 2½ mil instead of 4 mil) in a production EBR and in subsequent reproduction operations should be investigated. Thinner films offer the advantage of greater electrical capacitance but have lower dimensional stability and may be considered too difficult to handle in a production environment.

f) The possibility that a film manufacturer would produce a new special film for electron beam recording, with higher sensitivity but no worse resolution than for example, SO-438, should be

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investigated. However, it must be recognized that there is little likelihood that such a film would become commercially available in the near future.

g) The possibility of providing an electrically conducting backing for SO-438, or similar films, should be investigated. Such a backing need not be transparent nor particularly uniform if it is removed during film processing. Consequently, such a conducting backing should not greatly increase the cost of the film.

h) Assurances should be obtained from the Eastman Kodak Co. that the use of films similar to SO-438 (with perhaps a conducting backing and/or a thinner support) for some EBR applications will not jeopardize the availability of SO-219, since this film (or equivalent from other film manufacturers) must remain available for the more critical EBR applications.

i) The technical information presented in this report should be made available to all photographic film manufacturers and in particular to the Eastman Kodak Co. and the GAF Corporation who are known to be developing films specifically

for electron beam recording. Perhaps this can best be accomplished by publishing the results of this investigation in an appropriate technical magazine.

j) The use of Dielectric Film (DEF) in the ETL Cartographic EBR should be investigated. DEF is a nonsilver product which is sensitive to electron exposure but insensitive to light exposure and can be "developed" into an archival, high resolution, optical record by toner type processing. DEF offers the potential of high performance and cost effectiveness for the recording film itself as well as for its processing. Latent images on DEF can be read-out electronically by electron beam scanning techniques.

k) Reversal processing of images recorded in the ETL Cartographic EBR should be investigated. Although processing an image to produce a positive instead of a negative is more complicated, it may lead to significant costs savings in the subsequent reproduction of these images.

l) The use of reversal photographic films in the ETL Cartographic EBR should be investigated. Such films offer the advantage of recording directly positive images and the simplicity of normal film processing.

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APPENDIX

Triboelectricity, as it affects film
and film handling operations

Reproduced from Kodak Publication No. M-63

ELECTRICAL CHARACTERISTICS

The electrical properties of unprocessed aerial films are important because they are related to the static marks that sometimes appear in the developed image. Although these static patterns vary widely in their cause, occurrence, and appearance, each is due to a discharge of static electricity. The electrification of processed film also is important because it affects the film's capacity for attracting and holding dirt.

The generation and accumulation of static electricity is influenced by a great many variables. Consequently, there is, at present, no general solution to the problems it causes. Nevertheless, an understanding and application of the information in this section will minimize the occurrence of such problems.

ELECTRIFICATION

Types of Charge

A given area on an object becomes charged when it gains or loses electrons. Such a charged area will exhibit an electrical potential to ground, and its charge is referred to as "net charge." The term "polar charge" refers to the presence of equal and opposite charge densities on the two surfaces of a dielectric sheet. Charged areas will exert attracting or repelling forces on other objects.

Electrochemical Potential

Electrochemical potential is a function of material identity and when two dissimilar materials, having different electrochemical potentials, are placed in contact with one another, a non-equilibrium condition will arise. The difference in potential will cause electrostatic charge to move from one material to the other; this flow of charge will continue until the electrochemical potentials equalize, or until the materials are separated. Frequently, the two unlike surfaces are found to be electrified after separation. In general, separation of similar surfaces such as gelatin-from-gelatin results in less charge than separation of unlike surfaces, such as gelatin-from-base.

Charged materials seek to return to a neutral state by movement of electrons. If both materials are good conductors, they cannot be separated rapidly enough to prevent the charges from "flowing" back through the points of contact; the potential between the two materials thus disappears. However, if either or both materials are poor conductors, the charge will not flow back so rapidly through the contacting areas. It is then possible to retain some of the charge on the materials after separation. This suggests that the time for recombination of charge, that is, the time required for most of the charge to flow back through the last point of contact, is the criterion for defining a good conductor from the viewpoint of static.

Resistivity and Resistance

The surface resistivity of a material may be defined as the ratio of the potential gradient parallel to the current along its surface, to the current per unit width of surface. It is numerically equal to the surface resistance between two electrodes forming opposite sides of a square of any size. In general, resistance, R, in ohms, is related to resistivity ρ by the formula

$$R = \rho\frac{d}{wt} = \rho\frac{d}{A}$$

where: d is the length of the resistance element in the direction of current flow

w is the width of the resistance element

t is the thickness of the resistance element

A is the cross-sectional area perpendicular to the current flow.

(A = wt in Figure 44.)

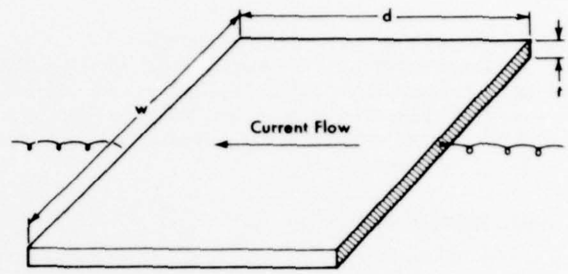

Figure 44
Resistance Element

For *surface* resistivity, the depth of penetration of the current into the surface depends on the material and its thickness. When considering a square element of surface (w = d) the dimensions of the square do not affect the value of surface resistivity because

$$\rho_s = R\frac{wt}{d} = R\frac{dt}{d} = Rt$$

Furthermore, thickness is a characteristic of a particular sample and may be ignored in surface resistivity measurements. Thus, ρ_s has units of ohms per square (or ohms for a square element).

Values determined for surface resistivity give some indication of the potential danger of static markings. A piece of material that is connected to ground will not hold a charge if it has a surface resistivity less than about 0.1 gigaohm per square. When the resistivity lies between 0.1 and 10 gigaohms per square, the charge will usually be dissipated except for very high speed operations (over 1,000 feet per minute). With resistivities between 10 and 1,000 gigaohms per square, static can be expected except with very careful handling and slow speed operation. And above 1,000 gigaohms per square it is almost impossible to prevent the accumulation of static charge. (In this discussion, ground is defined as a very large volume of conducting material; that is, a nearly infinite source or sink of electrical charge.)

Emulsions and gel backings are essentially alike in their resistivities. Protection by a gel backing or other antistatic layer is desirable because the resistivity of film base is many orders of magnitude higher than

1,000 gigaohms per square. Estar base particularly requires antistatic protection. Because of its different electric and mechanical properties, Estar base without antistatic protection may undergo greater electrification than cellulose ester base when separated from a nonsimilar surface, such as gelatin.

The *volume* resistivity of a material may be defined as the ratio of the potential gradient parallel to the current in the material to the current density. Expressed in ohm-cm it is numerically equal to the volume resistance between opposite faces of a centimeter cube of the material.

For volume resistivity

$$\rho_v = R\frac{wt}{d}$$

and ρ_v has units of ohms times length.

Volume resistivity of photographic film involves the highly resistant base layer. Typical values for unbacked cellulose ester bases at 50% RH are of the order of 10^{15} ohm-cm, while that for polyester base is in the order of 10^{20} ohm-cm.

AIR BREAKDOWN

During the separation of two surfaces, a disruptive spark may occur if the electric field across the gap becomes large enough to exceed the breakdown strength of the air. The sparking always takes place in air, either across the gap or along the surfaces, never within the body of the material. Much of the discharge energy is dissipated as light and this light will expose sensitized photographic materials and produce developable static markings.

FACTORS IN CHARGE ACCUMULATION

Surface Characteristics

Materials that have different electrochemical potentials will electrify when placed in contact. However, electrification is a surface phenomenon. Consequently, surface contaminants may often prove to be the controlling factor in electrification. Such contaminants include dust, dirt, oils, greases, moisture, absorbed gases, and the like.

Temperature

Elevating the temperature of a material raises the energy of its electrons. This increases the probability that these electrons will overcome the surface potential barrier and transfer to another contacting surface. However, for most substances, temperature changes of the order of 5 C have little effect on charge transfer. Localized high temperatures, caused by rubbing at contact points, may be one reason that sliding one surface over another increases electrification.

Contact Area

Since electrification takes place on contact, it may be increased by any factor, such as pressure or surface smoothness, that enlarges the real area of contact. Another reason why sliding increases electrification may be the fact that it increases the contact area. On the other hand, rough surfaces, such as those of shotblasted or sanded rollers, or of matte-containing emulsions, reduce the real area of contact and, accordingly, the overall charge density. Reduced atmospheric pressure tends to decrease the amount of air trapped between film and supporting surfaces thereby extending the contact area.

Heating a wound roll of film increases interlayer pressure and area of contact through thermal expansion and gelatin softening. This closer contact may persist even though the temperature is reduced before unwinding.

Surface Tackiness

The surfaces of tacky materials are soft and tend to flow when pressed against another surface. This increases the real area of contact and charge transfer.

Humidity

The moisture content of many materials varies with the relative humidity of the surrounding atmosphere. In some cases, the surface layer may become tacky as it absorbs moisture, thereby increasing the tendency toward electrification. For example, the increase in tackiness of emulsions or gel backings on exposure to higher humidities causes increased adherence between laps and greater electrification on separation. Moisture can also affect the properties of surface contaminants. These changes alter the characteristics of the outer layers to such an extent that often the magnitude and even the polarity of the transferred charge is changed. As a general rule, however, hydrophilic surfaces transfer more charge at low humidities than at moderate humidities up to about 60 percent. In addition, surface resistivity is higher at low humidity, so the retained charge tends to increase.

Time of Contact

The total amount of charge necessary to equalize the electrochemical potentials is transferred in a very short time at the contact points. However, if either surface is an insulator, considerably more time is required to transport this charge into noncontacting regions. Therefore, the amount of charge measured will depend on the length of time the materials have been in contact as well as on the conductivity of the higher resistance material.

Electric Fields

Electric fields can alter the potentials at the surface of two materials in contact and thus alter electrification. Such fields may originate externally, or they may result from charge within one or both materials.

FACTORS IN CHARGE DISSIPATION

Time and Conductivity

The amount of charge remaining on a body after it has been separated from another body depends on the instant the measurement is made and on the resistance between the body and ground. A charge can dissipate from an object by leaking across the surface or through the volume to ground. Or, it can be neutralized by ions of the opposite polarity that exist naturally in the air or are generated by a corona or spark discharge.

Temperature and Humidity

A large increase in temperature, or a small increase in humidity, will increase the conductivity of most non-metallic materials and thus allow a charge to dissipate more quickly.

Geometry

Geometric considerations may reduce or increase the voltage gradient to ground, thereby enhancing or retarding the flow of charge to ground. For example, sharp points or edges increase the voltage gradient in their vicinity.

* * *

The foregoing are but a few of the factors known to affect the accumulation and dissipation of charge. Evidence also points to the presence of additional influences which are not identified at the present time. In any event, this list is not complete, but it should give an idea of the complexity of static electrification.

The inherent electrical characteristics of photographic film, which consists of gelatin layers on a plastic base, make static a problem of long standing. Every effort is made in the manufacture of film to avoid static electrification. Machines are grounded, friction is minimized, humidity of the air is maintained at a level that gives the film an optimum moisture content, and operators observe elaborate handling precautions. Antistatic backings also may be used, as in the case of Estar base, where a gel backing is often used to minimize the possibility of static trouble.

EFFECTS OF STATIC

Air Breakdown

The most serious effect of static on unprocessed photographic film is the exposure of the emulsion by the light generated by breakdown of the surrounding atmosphere. The electric field necessary for air breakdown in the space between the electrodes depends both on the atmospheric pressure and on the distance between the electrodes. The potential needed for breakdown is lowered when the field is concentrated by highly curved surfaces such as points or sharp edges. It is also decreased when the spacing between film and conductor is reduced or when the atmospheric pressure is low, such as at high altitude.

It is sometimes possible to make objects to which a film might spark, such as rollers, of a material with sufficient resistance that the spark current, and thus the light output, is limited. Generally, if dark-adapted eyes can see the spark, there is enough light to expose many photographic films.

The relative spectral energy distribution curve of a spark discharge in air at standard conditions reveals that most of the energy is in the blue and ultraviolet region (Figure 45). All aerial camera films, as well as aerial duplicating films, are sensitive to this type of radiation. A film so exposed will show static marks after processing if the energy from the spark exceeds the threshold exposure level for the emulsion. The higher the photographic film speed, the greater the sensitivity of the film to static marking.

Static Patterns

Static marks on processed film can have many basic patterns (Figures 46 through 53). When the unprocessed film is positively charged, spot or "cloud" images are formed; when it is negatively charged, the result usually is a branched image. Often the distance between repetitive static marks will be a clue to some foreign material on the surface of a roller over which the film had passed prior to processing. In such a case, the marks repeat at a distance equal to the roller circumference.

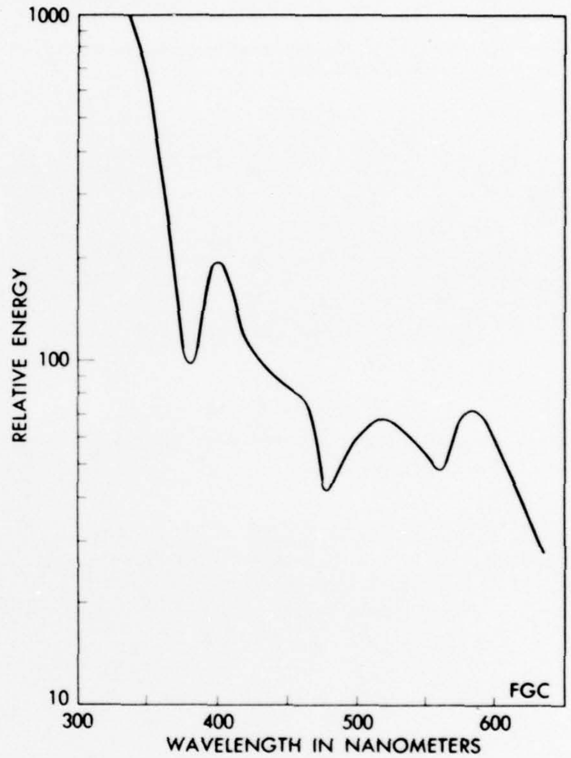

Figure 45

Relative Energy Distribution of Spark Discharge

Discharge in air at standard temperature and pressure

Dirt Attraction

Film carrying a static charge will attract and hold particles of dust and dirt. Unless the charge is neutralized, removal of the adhering particles is almost impossible. Nonelectrostatic cleaning methods merely redistribute the dirt over the surface or, at most, remove the dirt temporarily and then allow it to redeposit on the film. Static is similar to magnetism in that likes repel and unlikes attract.

Hazards

A static discharge can cause the ignition of flammable vapors and these may ignite with explosive force. The static charge will accumulate on a reasonably conductive surface, then discharge through the atmosphere with sufficient energy to ignite the gases that are present. Careful connection to ground potential prevents

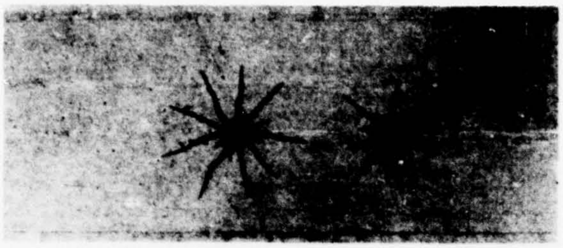

Figure 46
Typical Static Markings on Film

Markings caused by discharges between a small nearby object and a negatively charged film.

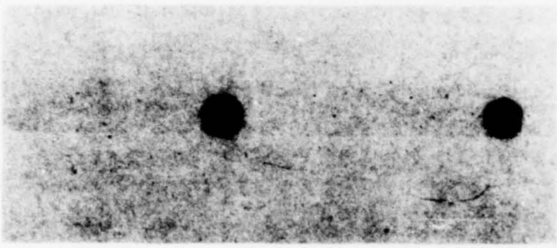

Figure 47
Typical Static Markings on Film

Markings caused by discharges between a small nearby object and a positively charged film.

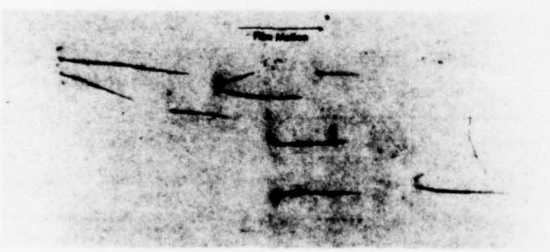

Figure 48
Typical Static Markings on Film

Markings caused by discharges between a roller and a negatively charged film.

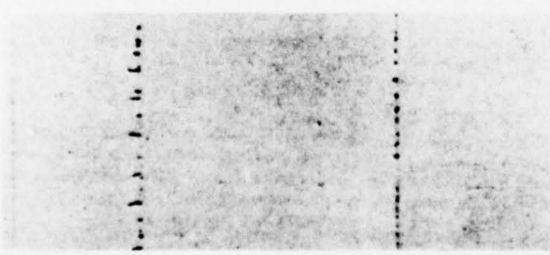

Figure 49
Typical Static Markings on Film

Markings caused by discharges between a roller and a positively charged film.

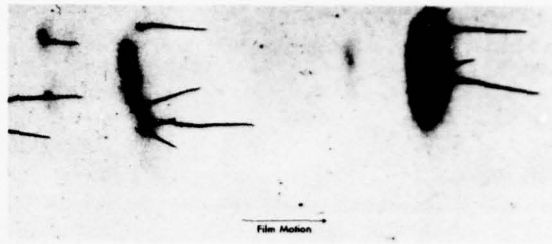

Figure 50
Typical Static Markings on Film

Markings from discharges in unwinding from a supply roll with the leaving strip of film having a negative charge.

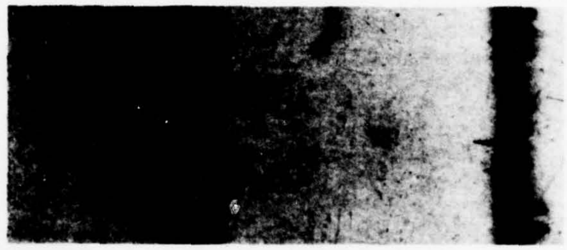

Figure 51
Typical Static Markings on Film

Markings from discharges in unwinding from a roll of film having a positive charge.

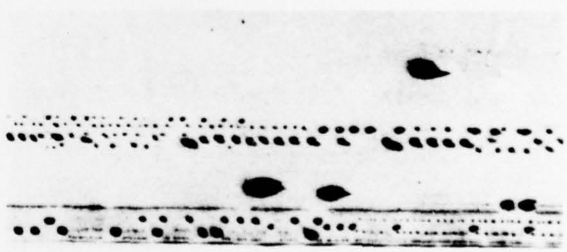

Figure 52
Typical Static Markings on Film

Markings caused by discharges generated by rubbing film with hands.

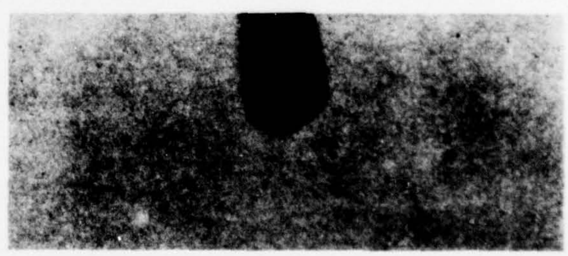

Figure 53
Typical Static Marking on Film

Marking caused by discharge during unwinding of a roll having a high moisture content.

the accumulation of a charge on a conducting material. Discharges from high resistivity materials usually have insufficient energy to ignite most vapors. However, each situation must be evaluated as a unique case both initially and periodically thereafter because changing product characteristics or machine conditions may create a hazard.

PROBLEMS IN FILM HANDLING

Roller Transport

When an insulating film or paper web travels over one or more rollers a spark may form in the nip on the exit side. Marks caused this way appear across the developed film as intermittent lines. On negatively charged film, the "tails" of these marks point in the direction the film was traveling (Figure 48). Attempts to avoid such sparking by blowing ionized air into the nip have never been successful.

Constructing the roller of a material that gives an exiting charge that is less than the entering charge is an effective remedy; additionally, a roller material with a high enough resistivity can limit the possible spark energy to a level that will not expose film. However, the material must be conductive enough to prevent the buildup of charge on the roller–a resistance from the surface to ground of between 0.1 and 10 gigaohms is usually satisfactory except for high-speed operations.

Rollers of plush cloth treated with Triton X 200* or rollers made from Tamol*-milled Synthane** work well with many film and paper surfaces. If a resilient roller surface is desired, polyurethane containing 5 percent Catanac LS*** is a good choice. This latter material usually prevents static markings, although its efficiency at very low humidities has not been thoroughly tested.

Unwinding from a Roll

In a film roll, the emulsion usually is in contact with a backing material. Although Kodak film products are designed to minimize charge transfer as far as possible when equilibrated with 50 percent relative humidity, they may electrify when separated. Tightly wound rolls have high interlayer pressure and, if unwound at high speed, may spark in the nip (Figures 50, 51). The best remedies for this situation are less-tight winding and slower speed of unwinding. The ambient relative humidity during unwinding has little effect.

The likelihood of sparking during unwinding also is increased if the roll has been warmed above about 25 C. This is true even if the roll is subsequently unwound at a lower temperature. And unwinding of tacky film of high moisture content may produce blotchy "moisture" static (Figure 53).

It is possible to obtain a comparative measure of the charge produced in unwinding a film roll by determining the voltage built up on the roll as the film laps separate. The voltage measured during unwinding is related to the intimacy of lap contact as affected by the original winding tension. It is also related to film tackiness, to storage conditions and, to a lesser degree, to the speed of unwinding. To illustrate, a roll unwound after normal storage may show a safe, low potential; but if unwound after storage for one day at 50 C the same roll may show much higher voltages. Furthermore, the moisture content of the roll has some influence but the ambient relative humidity does not, because of the time required to change film moisture content.

Winding a Roll

Relatively small charges on a web may combine as successive laps are wound on the roll. Eventually, the charge may build up to a point at which breakdown occurs over one of the roll surfaces or from the roll to a nearby operator or other grounded conductor. On the other hand, it is also possible that static charges that remain on the film as it is wound into a roll will dissipate without discharge markings in a reasonably short period of time. When this is the case, most of the charge leaks away in a matter of minutes after winding has stopped.

When film is being rewound as in a camera, for example, charge may flow along the web to the last object contacted before the windup. This may cause a spark to a roller, a platen, or even the supply roll. In some cases, only a partial discharge takes place, so that some of the charge remains in the takeup roll. For this reason, caution should be exercised when subsequently handling the rewound roll.

An effective remedy for this problem is reduction of the charge on the web to as low a level as possible before windup. This can be accomplished by proper design of the last roller to contact the film or by installation of a discharging device before windup. (See Methods of Controlling Static, p. 40.)

Sliding Contact

Sliding contact is usually a very high charge transfer mechanism. It should be avoided wherever possible. Such slip may exist between layers of film, or between a web and a misaligned roller or a roller that has a high inertia or defective bearings. High inertia causes slip during both acceleration and deceleration; defective bearings often cause intermittent slip as they alternately jam and release. Pinch rollers must slip because of deformation of their peripheries. Even good conductors may be charged by friction, but the electrons transfer easily through the conductor and the charge is readily grounded. A poor conductor, such as photographic film, may build up and retain its charge in local areas.

Other common situations where slip can generate charge are encountered with pressure pads used in cameras to position the film during exposure, and with light locks where the film slides over light-blocking surfaces as it emerges from a cassette or similar container. The charge may slowly dissipate through surface leakage currents, ionize the air in the immediate vicinity and discharge as a corona, or may cause a spark to a grounded object. Sliding contact with an individual's hand often generates a static discharge which may produce a continuous row of small static marks similar in appearance to a string of pearls (Figure 52).

Each of these situations has caused numerous static problems. In attempting to avoid similar occurrences, surfaces contacting the film should be constructed of

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*Trade name–Rohm & Haas.
**Trade name–Synthane Corp.
***Trade name–American Cyanamid.

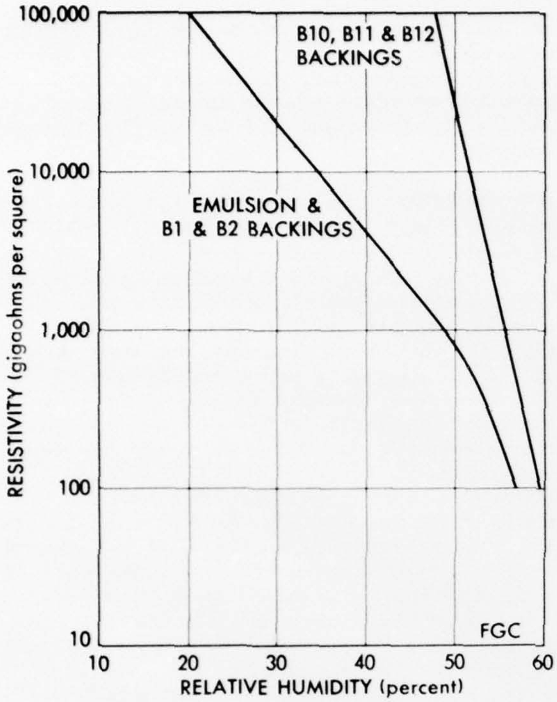

Figure 54
Typical Surface Resistivity

Data taken at 22 C. Curves are typical for Kodak aerial films. Individual films may show variations in magnitude of resistivity but the curve shapes are similar.

materials that minimize charge transfer. Furthermore, contact pressures and slip speeds should be kept as low as is consistent with other operating parameters.

Film Handling in Aerial Cameras

In aerial photography, several factors may combine to increase static electrification problems. One of these, which has many complications, is reduced air pressure at the higher altitudes. If the camera is mounted in an unpressurized aircraft bay, the film and camera will be exposed to a partial vacuum. As the pressure decreases, the film loses moisture due to outgassing and its electrical surface resistivity rises, making it more prone to static (Figure 54).

Under reduced atmospheric pressure, ions are more readily produced in air by charged film to act as carriers for a static discharge. Consequently, a film-marking discharge can occur more easily than under normal pressure. However, as the degree of vacuum increases and the carriers decrease in number, the discharge spreads out, so a discrete mark is less likely to occur.

Another altitude-dependent property is the air breakdown voltage, which drops approximately one-third over the first 10,000-foot increase in elevation. Less charge buildup, then, is needed for a spark to occur.

There is also a temperature drop at higher altitudes. Aerial reconnaissance involves camera compartments that may be unpressurized, but which usually are heated to facilitate mechanical performance of the camera. When air is heated its relative humidity is proportionally lowered. Film as manufactured, however, has an equilibrium moisture content near 50 percent RH. Thus, as it unwinds in the camera, the film gives up some of its moisture to the surrounding low-humidity atmosphere. If the film traverse is halted prior to and during the exposure, the film reaches equilibrium with its surroundings and the transfer of moisture ceases until more fresh film is unwound from the supply roll. As a consequence, the moisture content of the air inside the camera fluctuates in a complex manner.

It is apparent, then, that the static propensity in an aerial reconnaissance camera depends, among other factors, on the pressure, temperature, and relative humidity of the air in the camera. It also depends on the moisture content and rate of advance of the film.

METHODS OF CONTROLLING STATIC

There are a number of basic rules to be observed when designing apparatus for handling photographic materials. Adherence to these rules will minimize static electricity (Table 17).

Prevention of Buildup of Charge

The foremost method of preventing the buildup of electrostatic charge is to make all the materials relatively conductive and to keep them connected to ground. Increasing the relative humidity is an effective way of doing this for those materials or coatings that depend on moisture content for their conductivity. Typical conductors of this nature are the emulsion and backing layers, and many of the antistatic coatings and backings used on photographic films. For such materials, the surface resistivity (the reciprocal of the conductivity) varies greatly with relative humidity (Figure 54). On the other hand, however, relative humidities greater than 60 percent may cause tackiness which tends to increase charge transfer. Ferrotyping also may be induced under the influence of the greater moisture content of the gelatin layers.

In specific cases, electrification may be prevented by allowing the film to contact only those other materials that have similar electrochemical potentials. Thus, it

TABLE 17

BASIC RULES FOR MINIMIZING STATIC ELECTRICITY ON PHOTOGRAPHIC MATERIALS

- Avoid sliding contact.
- Avoid pinch or "wringer" type rollers.
- Avoid sharp corners and edges near charged insulators.
- Use power-driven unwinders to prevent cinching film rolls.
- Use smooth acceleration and deceleration and low-inertia rollers to minimize slippage.
- Use lowest possible web tension.
- Keep contact with insulating materials to a minimum.
- Use enough force to turn idler rollers at all times—bearings must not bind.
- Use rollers having less than 0.1-gigaohm resistance surface to ground. Note that plastic bearings in the path to ground usually have high resistance.
- Use nondeforming rollers to avoid sliding contact.
- Roughen the roller surface.
- Carefully align rollers to prevent slippage.

TABLE 18
EFFECT OF MATERIAL ON ELECTROSTATIC CHARGE

Roller Material*	Against Emulsion and B1 & B2 Film Backings	Against B10, B11, & B12 Film Backings	Remarks
Cloth plush glued to grounded metal roller; plush treated with Triton X 200	Best material for removing charge	May add charge	Prolonged use may cause dirt problem on film.
Polyurethane treated with 5% of Catanac LS	Average material for removing charge	May add charge but less than treated plush	Long wearing. No dirt problem. Catanac LS may leave surface after a long period at sustained high pressure and high speed.
Tamol-milled Synthane	Removes small amount of charge	May add a small amount of charge	Resistance makes a bright static spark unlikely. Corona glow may fog photographically fast film.
Plain metal roller	Normally adds a small amount of charge, but can add a large amount if pressure is high as in pinch rollers, or with slippage	Same as for emulsion and B1 & B2 film backings	A roller material that removes charge should be used after no more than 10 successive metal rollers. Fewer, if high pressure or slippage is present.

*Resistance from roller surface to ground must be less than 0.1 gigaohm. Avoid rubbers and untreated polyurethane roller materials.

is feasible to select rollers made of materials that either do not add a charge to the film or actually reduce any charge that may be present (Table 18).

Of course, electrification could be minimized if the film were not allowed to touch any other object. Although completely preventing contact is impractical, reducing the degree of contact as much as possible will serve to reduce the degree of electrification. This is the mechanism by which matte in a film surface layer helps to keep electrification at a low level.

Electrification is almost always increased by severe handling. Thus, high rewind speeds, rubbing the film, high winding tension, and similar practices usually increase static generation. On the other hand, care in assuring proper alignment of rollers and other parts, keeping the area of surfaces against which the film will slide to a minimum, and reduction in the speed of handling will help to diminish the generation of charge.

Neutralization of Charge

One way of reducing an existing charge is to apply a neutralizing charge of the opposite polarity. The techniques usable on unprocessed film are limited to those that will not fog the film. Several methods exist.

Materials Contacting Film. Rollers and other surfaces that contact the film may be constructed of materials that will add charge to the desired polarity or drain away existing charge (Table 18). Such surfaces are known as "discharging" surfaces because the charge on the web, as it breaks contact, is less than the entering charge.

External Electric Field. Another method applies an external electric field to the region of charge transfer.[66] Thus, the amount of charge exchanged is controlled. The most simple technique involves the application of voltage to one roller of a pinch-roll assembly while grounding the other roller. The rollers must have a resistivity less than 1 gigaohm-cm. Voltages less than 50 volts applied to a cloth-covered roller opposite a grounded metal roller are adequate (U.S. Patent 3,671,806) and make this method usable on unprocessed film.

Conducting Brush. Charge can be applied to film with a brush. A soft conducting brush, connected to a DC power supply, should contact the film as the latter passes over a grounded conducting roller. Nylon bristle brushes, made sufficiently conductive by soaking them in Avitex R,* can be used on unprocessed film. Full control requires up to 2,000 volts on the brush.

Ionized Air. A neutralizing charge can be obtained by providing ionized air in the vicinity of the charged film, so that the "net" electrostatic charge will attract the proper number of ions of the opposite charge. Generally, this must be done at a place where the film is not in contact with grounded rollers or other parts. Such grounded objects contain an image charge which reduces the attraction of neutralizing ions. A "polar" charge on the film gives rise to very little external field so that special arrangements are required to attract ions in this case.

Sources of alpha radiation will ionize air. These can be used on the back of sensitized film and, to a limited extent, on the emulsion. They can also, of course, be used on processed film.**

Air can be ionized by an electrical corona and numerous devices have been designed for this purpose. However, these usually emit light so their use is restricted to processed film. The most convenient devices in this category are needle bars or grounded tinsel. These units consume no power but, instead, use sharp points to concentrate the electric field from the charge on the film. The field is sufficiently concentrated to break down the air and generate ions.

If the film does not have a high enough initial charge, there is no ionization; or, if the charge has been reduced to a certain level, ionization ceases. This usually occurs when the film potential is between 500 and 2,000 volts. The amount of ionization is also dependent on the sharpness of the points, their closeness to the charged film surface, and the number of points within

*Trade name—E. I. Du Pont de Nemours and Company.

***Nuclestat* bars containing Americium are available from Nuclear Radiation Development, Inc., 2937 Alt Boulevard North, Grand Island, N.Y. 14072.

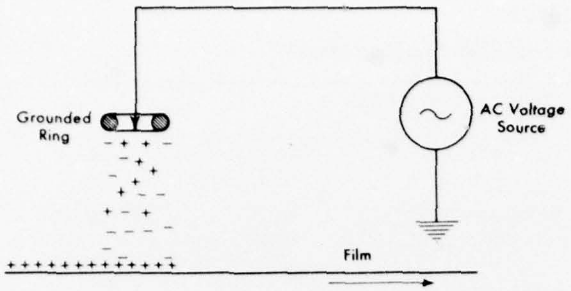

Figure 55
Discharge by Electric Static Bar

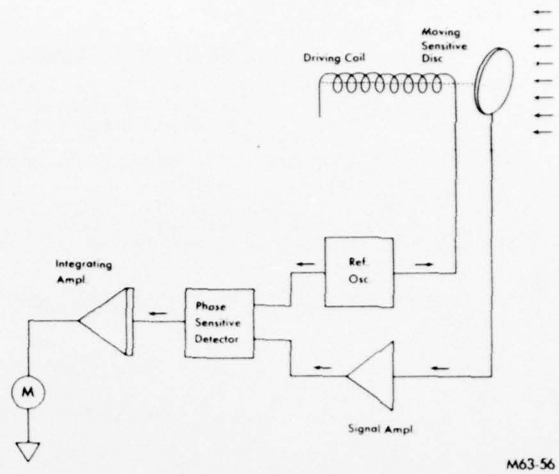

Figure 56
Field Meter

a given space. Obviously, the tinsel must be metal, not the plastic, decorative type.*

More complete charge neutralization can be obtained by putting an AC voltage of 3 to 10 kV on sharp points. Inductor bars often are used for this purpose. A wire connected to a high AC voltage supply approaches, but is not connected to, the sharp points. It induces a potential on the points, but the current is limited to safeguard personnel (Figure 55).

In another configuration, a needle connected to high-voltage AC is located in an orifice with a high-velocity airstream blowing the ions to the desired location. This appliance, known as a "Jet Ionizer," can be light-locked for use on sensitized materials (U.S. Patent 3,409,768).

The KODAK 10-inch Dust and Static Removal Unit, Model A2-K, is designed to remove dust and electrostatic charges from nonsensitized photographic materials such as filters and processed negatives. A Static Eliminator Power Unit is an integral part of this device. Available accessories include inductor bars of 4- and 18-inch lengths, brushes equipped with inductor bars, and associated cables and connectors.

Hazards. Electrically powered corona devices may be dangerous when used in areas that contain explosive vapors. Special precautions permit them to be used in certain areas, but such applications must be carefully considered.

DETECTION AND MEASURING INSTRUMENTS

Charged particles cannot be easily identified or counted. For this reason, their external effects must be used for detection and measurement. Measuring methods that respond to the field from a charged object can be separated into two main groups:

1. Those that detect only *part* of the field from the charged object, such as electroscopes, electrometers, field meters, and noncontacting electrostatic voltmeters.
2. Those that measure the *entire* field from the charged object, such as a Faraday can or cylinder coupled to a measuring instrument.

The basic instrument used in determining the electric field of a charged body is the field meter, consisting of a pickup connected to an AC amplifier (Figure 56). The sensitive disc, because of its motion, has a variable signal induced on it. The signal is amplified and its phase compared with the driving coil mechanism. The resulting output, integrated and measured by a voltmeter, is proportional to the electric field at the sensitive disc in volts per unit length.

A field meter measures the electric field from the static charge on an object. At normal atmospheric pressure, the electric field from a charged film can cause air breakdown when it ranges between 2,000 and 10,000 volts/cm (measured in "free space"). Above 10,000 volts/cm, breakdown is nearly certain to occur. These values become lower as the ambient pressure is reduced.

If the field meter pickup is driven to the same potential as the charged object by suitable feedback, the instrument becomes a noncontacting electrostatic voltmeter with the output measured in volts.

To calculate the average charge density on an object in a Faraday can, the reading of an electrometer connected to the can is divided by the area of the charged object.

Field meters and voltmeters are commercially available from Monroe Electronics, Inc., 100 Housel Avenue, Lyndonville, New York 14098, and voltmeters from Trek Inc., 8460 Ridge Road, Gasport, New York 14067, and from other companies. Electrometers and high-resistance measuring instruments are commercially available from Keithley Instruments, Inc., 28775 Aurora Road, Cleveland, Ohio 44139, and other companies.

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An attempt has been made here to discuss the practical aspects of the subject of static electricity as it affects film and film-handling operations. Elementary texts that explain the basic laws of electrical charges and their behavior,[67] as well as comprehensive treatments that delve more deeply into electrification phenomena,[68] are available. An extensive bibliography on electrostatics is also available.[69]

*Metal tinsel is available from National Tinsel Mfg. Company, Manitowoc, Wisconsin 54220.